# Cosmic Muon Noise in the NPDGamma Detector Array

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Anomalous outlying data points have been observed in the NPDGamma CsI detector array while attempting to measure the magnitude of random detector noise. It is hypothesized that these data points are caused by cosmic rays depositing energy in the detectors.

To test this hypothesis, anomalous points were first defined to be any points lying more than six standard deviations away from the average value (pedestal). The standard deviation and average value was recalculated every 50 ms for each detector independently. For a random Gaussian distribution of noise the percentage of points lying outside of this area is approximately 0.00005%. For a 10,000 pulse run (500 seconds) the number of data points outside of this range should be:

$$5 \cdot 10^{-7} \cdot 48 \text{ detectors} \cdot 10000 \text{ pulses} \cdot 100 \text{ data points per pulse} = 24 \text{ data points} \tag{1}$$

If the observed anomalous points were from random Gaussian noise, then only 24 outlying data points should be detected for every 8 minutes of data acquisition. However, the actual resulting number of outliers for a given 8 minute run is approximately 179,000. This leads to the belief that these points are not just noise. It is hypothesised that they are caused by cosmic radiation. The purpose of this paper is to reinforce this hypothesis.

Muons are the dominant form of cosmic radiation at the earth's surface and can be detected with CsI(Tl) detectors. At 54 degrees north latitude, during maximum solar activity at sea level, the fluence rate for muons is 0.019 particles$\cdot$cm$^{-2}$s$^{-1}$ [1] and the median energy for these particles is 4 GeV.[3] However, at higher altitudes with thinner air there is a higher flux of cosmic radiation and the mean energy is a bit higher. It is calculated that, assuming Los Alamos is at 7400 feet with an air pressure of 786 g/cm$^2$, muon flux intensity is 60.8% higher than at sea level.[2] This yields a new fluence rate of 0.0306 muons per square centimeter per second. Muons typically lose 2 MeV g$^{-1}$cm$^{-2}$ as they pass through the atmosphere.[3] So a 4 GeV muon at sea level should have had 6 GeV mean at the top of the atmosphere. It follows that at Los Alamos' altitude, the muon should have 4.4 GeV of energy left. If the mean energy scales accordingly, then the mean muon energy at LANL is also 4.4 GeV. It turns out that this slight change in intensity is inconsequesntial because the energy deposited in CsI does not change a significant amount for muons with energy higher than about 1 GeV.

The expected number of detections due to muons in the NPDG detector can be approximately calculated based on the muon fluence rate and the cross sectional size of the detector array. A detection is defined as any data point outside of 6 standard deviations away from the average. One individual CsI detector has a surface area of 264 cm$^2$ on a side. If it is assumed that all detected rays are incident from the top of a detector and the ray can freely pass through a detector and not lose a significant amount of their total energy, then the cross sectional area of the detectors is 12,670 cm$^2$. The total number of detections expected for a 500 second run is:

$$12670 \text{ cm}^2 \cdot 0.0306 \frac{\text{particles}}{\text{s} \cdot \text{cm}^2} \cdot 500 \text{ s} = 193500 \text{ particles} \tag{2}$$

This theoretical value is multiplied by 4/5 since the NPDGamma detector array only samples for 40 ms out of a 50 ms period. Taking this into account, 155,000 particles are expected to be detected for the 500 second period. This agrees with our measured value of approximately 179,000 detections per 500 second period. However, this value is only a rough estimate and does not account for current solar activity, geomagnetic ridgitiy (the ability of the earth's magnetic field to deflect cosmic particles) of the Los Alamos atmosphere, or atmospheric pressures at the time of measurement. More importantly, it also assumes particles may not enter the sides of the detector, whereas in reality the muon flux obeys a $\cos^2\theta$ relationship with the angle of incidence [3] and could enter the sides of the detector below the face.

Muons usually do not deposit all of their energy in one detector and stop. Rather they will deposit an amount based on their energy as well as the thickness and type of the material they pass through and then continue on with most of the energy they had upon entrance. Therefore, by polling two vertically adjacent detectors that are farthest apart (44 cm) for potential cosmic events with the stipulation that both detectors must simultaneously measure the event, this sets a limit on the angle of incidence to $\approx$20 degrees off of the vertical. This filtering will help simplify analysis since it puts a constraint on the maximum amount of detector that each muon will travel through and will at the same time reduce detecting muons that pass through only a small part of a detector or enter from the side. There is no limit, however, to the minimum amount of detector that the muon may travel through.

The concept just described can be applied to all NPDG detector pairs. The closer together a pair of detectors is though, the less effective the filtering will be due to the increased solid angle formed by the two detectors. It follows that the detectors at the sides of the array will see the most detections since they are closest together and the detectors at the center of the array will see the least detections, since they are farthest apart. Figure 1 shows such filtered data in a histogram that represents a top-down view of the detector array as would be viewed if standing in front of the spin-flipper. Each bin represents a vertically adjacent pair of detectors. As expected, many more hits occur at the sides, where the detectors are closest together, while many less occur in the center, where the detectors are farther apart. The high number of detections in the second detector pairs in rings two through four and in detector pair one in ring one are attributed to exceptionally low noise levels in those particular detectors. Specifically, these detectors are numbers 10, 23, 35, and 47. All of these detectors show standard deviations in the 0.2 mV range, while the rest of the detectors have standard deviations ranging around 0.3 mV. This allows lower energy events to be detected which would normally blend in with the noise. This results in a higher count rate than in higher-noise detectors. In fact, on a run-to-run basis, the heights of the bins relative to each other stays about the same and are inversely proportional to their standard deviations. The fact that these detectors are grouped adjacent to each other seems to be merely coincidence.

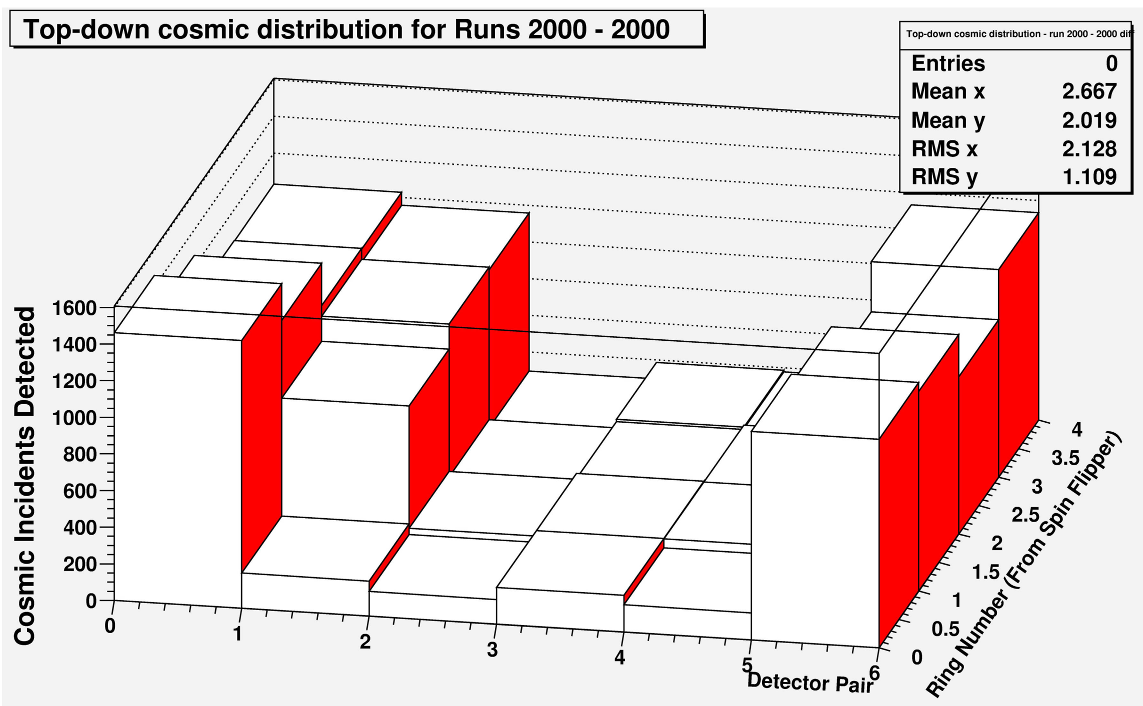


Figure 1: Histogram of cosmic events in the detector array as would be seen standing in front of the spin flipper and looking down at the top. Each bin represents a pair of vertically adjacent detectors. A cosmic event is defined as any data outside of 6 standard deviations occuring in two vertically adjacent detectors during the same 400$\mu$s period.

Individual detectors were also examined to determine if the voltage spectrum seen in the detectors agrees with the energy spectrum of cosmic muons. Figure 2 shows the distribution of detector output values for all data points that were outside of six standard

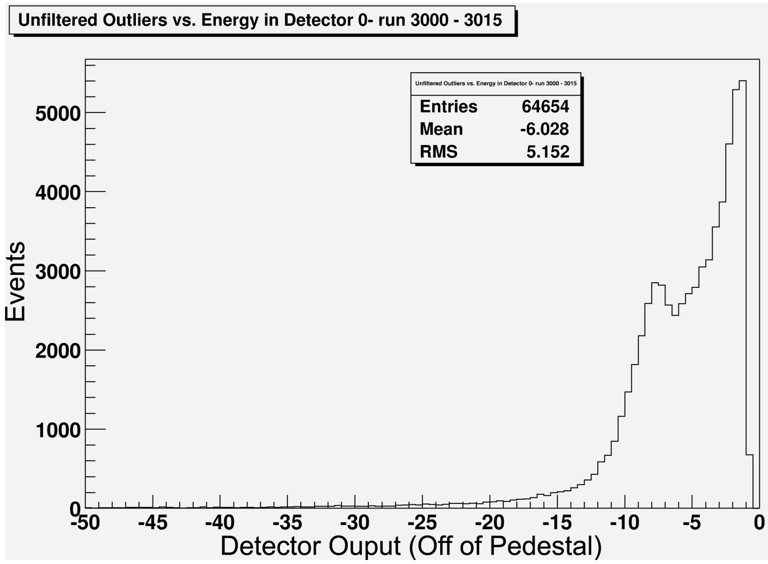


Figure 2: Histogram of cosmics detected (events occuring outside of six standard deviations from the average) in 8000 seconds vs detector output in mV. In this detector, one mV is corresponds to an energy deposition of about 12.8 MeV.

deviations from the average (pedestal) value. The sudden cutoff at the right is from the constraint that only events that are six standard deviations from the pedestal voltage are considered. This is unavoidable because the muon energy spectra goes to zero and blends into the detector noise found near the pedestal voltage. Figure 3 shows the energy spectra for muons at an air pressure approximately equal to the air pressure at Los Alamos; this graph predicts an exponential decay of intensity as muon energy increases. This same relationship is approximately seen in figure 2, except for the presence of a small peak centered near -8 mV. This peak is understood by examining the energy loss of a muon through CsI. Figure 4 gives the muon loss of energy as a function of distance through CsI(Tl). [6] The total energy deposited by a single muon in a CsI detector is determined by looking at the energy of the incident particle and the amount of material it passes through. Muons with energies $>$ 1 GeV lose a nearly uniform amount of energy through the detectors at a rate of $-\frac{dE}{dx} \approx 6\mathrm{MeV\ cm}^{-1}$. It follows that for a 16.2 cm thick detector, any muons with energies above about 1 GeV should deposit a total of $\approx$ 97 MeV in the detector. For this detector, this energy translates to a -7.6 mV signal off of the pedestal,

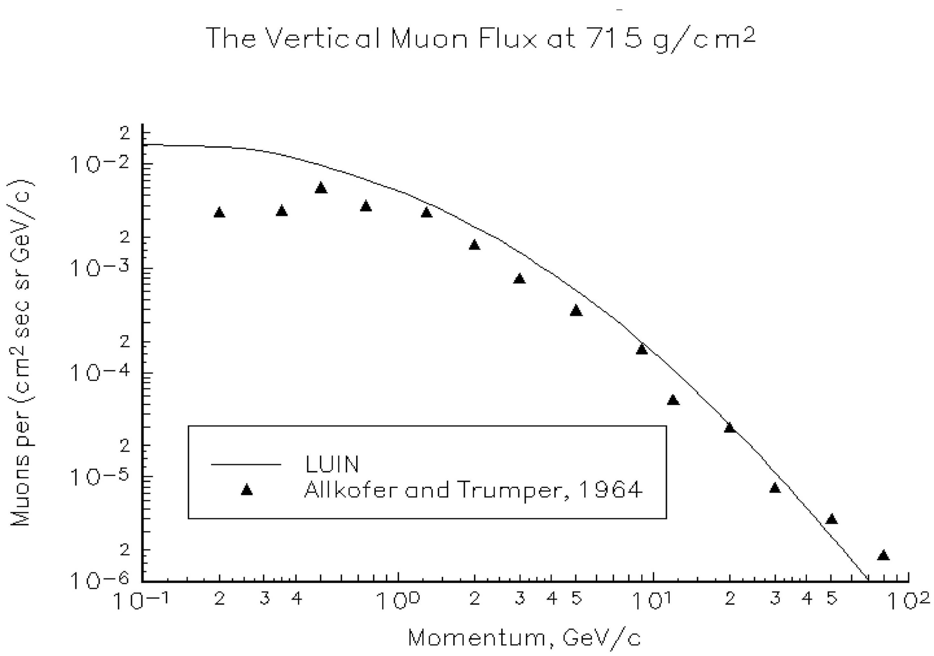


Figure 3: Vertical muon spectrum at 715 $\frac{g}{cm^2}$. Los Alamos is at approximately 786$\frac{g}{cm^2}$. Sea level is at 1030$\frac{g}{cm^2}$.[7]

which corresponds to the peak in figure 2. The width of the peak is attributed to some noise in equipment electronics and the fact that muons incident at different angles will go through different thickness' of detector and so can deposit a broad range of energies. Events with energy significantly lower than -7.6 mV from the pedestal are most likely multiple cosmic rays incident on the same detector during the 400 $\mu$s sampling time. Since muons are allowed to come in with any angle, they may pass through varying amounts of detector and deposit varying amounts of energy, so it is difficult to discern any more useful information about the muon spectrum from this histogram.

Figure 5 shows an energy vs. event histogram from a typical NPDGamma detector with non-vertical events filtered as described earlier. The selected detector is the same one as described in the previous paragraph for comparison purposes. It is also at the center of the array and therefore has the largest distance from its vertically adjacent detector which will provide the most effective filtering of non-vertical cosmics. The filtering limits muons to a 20 degree maximum angle of incidence so that the absolute maximum distance

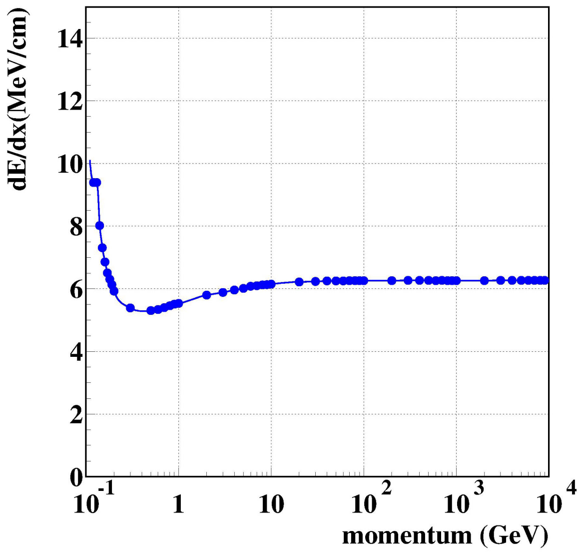


Figure 4: Energy loss of muons in a CsI(Tl) crystal (GEANT simulation) [6]

of travel through one detector is about 16.6 cm. Furthermore, muons must have enough energy to totally pass through the top detector in order to be detected by the detector directly below it. The result should be an energy spectrum of the detected events that have come from a nearly vertical angle and have a minimum energy of roughly 85 MeV, based on the minimum energy required to totally pass through the top detector and be detected in the lower detector. This filtering does not totally eliminate the presence of low energy events, since some muons can still travel through portions of detectors, but it should significantly reduce them. Figure 5 agrees with expectations – a distinct hump is seen around the -8 mV region of the spectrum. However there is also another peak seen near the pedestal voltage which is not explained by this argument. This peak is hypothsized to be caused by separate low energy muons that enter the sides of both detectors during the same 400 $\mu$s time bin and are then registered as one event when there are actually two independant events occuring. This could be eliminated by either shortening the time bins or by measuring coincidences with detectors that will reduce the number of particles that enter from the sides.

To test this hypothesis, another flat CsI detector was added to the NPDGamma de-

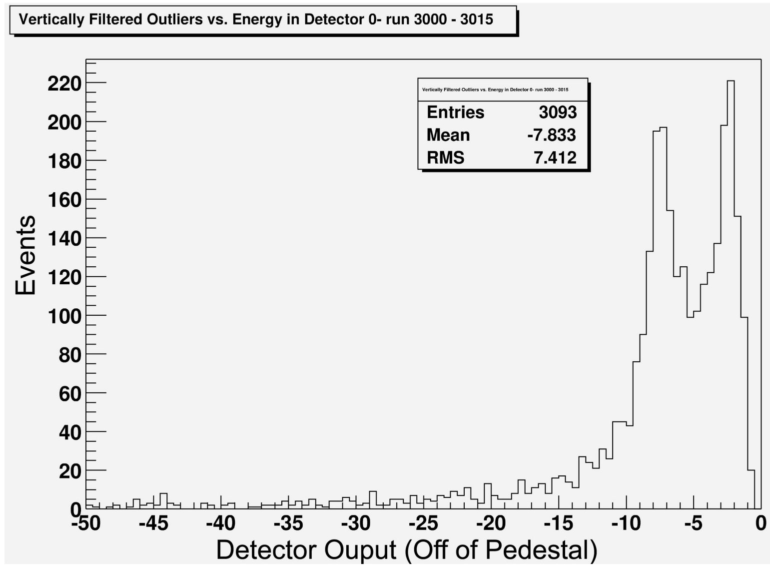


Figure 5: Detector output spectrum when events are filtered such that two vertically adjacent detectors must register an event in the same time bin. Note the lower relative intensity of the peak near 0 mV as compared to the unfiltered spectrum in figure 2.

tector array directly above detector zero. This extra detector is about 0.5 cm thick and has a surface area roughly equal to that of a face of an NPDGamma detector. The output of this detector was routed to a gate which was set to send a pulse after a certain threshold voltage was output by the flat detector. This threshold voltage was set so that the frequency of events was about 5 per second. The output from the gate was then interfaced with the NPDGamma data acquisition unit. By defining an event such that the flat detector and both of NPDGamma detectors below it had to register an event during the same time bin filters out almost all comic rays that enter through the sides of detectors to produce a 'false' event. Figure 6 shows the output spectrum with the new event definition. As expected, almost all of the low energy events from cosmic rays entering the sides of detectors were eliminated, leaving a very definite peak about -8 mV. This peak is fitted with a gaussian curve, shown in blue. The mean of the gaussian is -7.52 mV with an error of 0.9%. Error was determined from $\frac{\sigma}{\sqrt{N}}$. Under the same filtering scheme, detector 2, which is in contact with its vertically adjacent detector and is therefore subject to less effective filtering, was still able to determine the peak of the gaussian

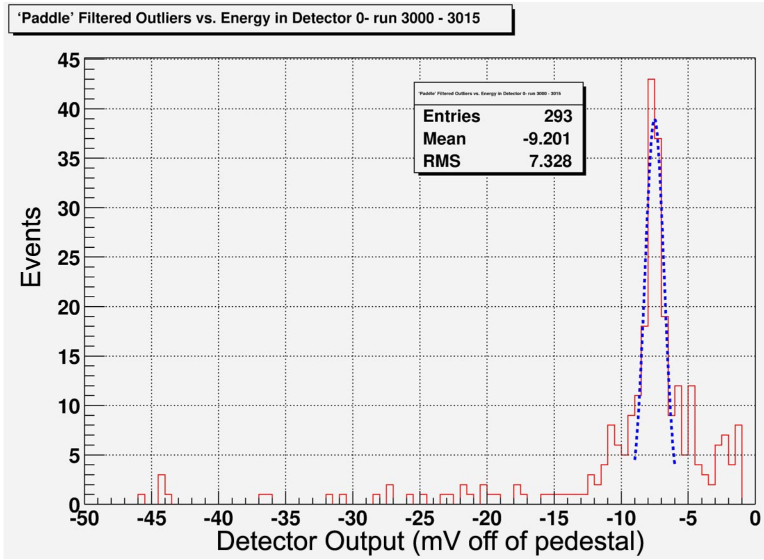


Figure 6: Detector output spectrum when events are filtered such that two vertically adjacent detectors and a vertically adjacent flat 'paddle' detector must register an event in the same time bin. The blue curve is a gaussian fit to the clearly defined peak, which is centered at -7.52 mV. This agrees with the expected peak to better than 1%.

with an error of 1.0% for the same sampling period. Events with energy significantly higher than the the peak are most likely caused by an air shower depositing many muons in a short time span so that their energies become combined within a time bin. Events with energies significantly lower than the peak are likely caused by the small statistical chance that all three detectors register an event at the same time from separate muons giving the opportunity for a low energy event to be counted in detector 0. These types of events could both be reduced or eliminated if the detectors had a higher sampling rate, in which case the peak should be even more defined.

Finally, it is expected that the detectors on the top of the array will stop lower energy muons and provide some shielding to the detectors on the bottom, so that more muons should be counted by the detectors on the top than on the bottom. Figure 7 shows a histogram of total cosmics detected vs. detector number. The bars shaded in black denote detectors that are on the top of the array, white bars denote detectors on the bottom. As expected, the detectors on top yielded more detections overall than the detectors on bottom. Note that the four outstanding peaks correspond to the detectors with the least noise as mentioned eariler.

In conclusion, it has been observed that the anomalous data found in the NPDGamma CsI detectors is certainly not random in nature and has characteristics that would be expected to be caused by cosmic muons. This has been demonstrated by examining the intensity of the anomalous data points, their energy spectrum in the detectors, and by examining their exptected behavior based on the geometry of the NPDGamma system and the known geometry of incoming cosmic muons. Suggestions to further enhance the observed muon energy spectrum were also suggested if the need to do so ever arose.

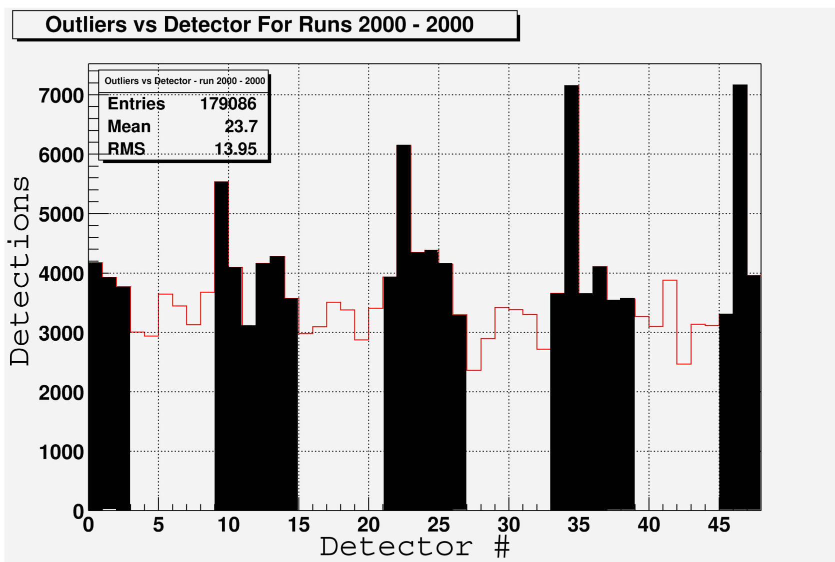


Figure 7: Histogram of total cosmics detected in 500 seconds vs detector number. Black bars are detectors on the top of the array, white are detectors on the bottom. Detectors on top generally receive more hits than detectors on bottom due to shielding.

# References


[1] "Cosmic Radiation", Health Internet:http://hps.org/publicinformation/ate/q1322.html, October (2001).

[2] "Terrestrial cosmic ray intensities", Internet: http://www.research.ibm.com/journal/rd/421/ziegler.ht

[3] "Muons", Lawrence Berkeley National Lab Website, Internet: http://www.lbl.gov/abc/cosmic/SKliewer/Cosmic_Rays/Muons.htm

[4] Phys Rev D., Vol. 50, Part I, p1251, August (1994).

[5] Pascale et al. Journal of Geophysical Research, Vol 98, No A3, p3505, March (1993).

[6] Ikeda, Hitomi. "Development of the CsI(Tl) Calorimeter for the Measurementof CP Violation at KEK B-Factory," Ph.D. Thesis, NWU-HEP, (1999).

[7] O'Brien, Keran. "Computational Physics of Cosmic Ray Transport in the Atmosphere". Internet:http://www.arcs.ac.at/compsimul/innovlab/projekte/obrien_cpcrta.pdf.